Sub-microradian Pointing System Design for Deep-Space Optical Communications

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ABSTRACT

This paper summarizes NASA/JPL progress on sub-microradian pointing system design. Sub-microradian pointing has been found to be critical for the deep space optical communications from earlier studies. The objective of current effort is to develop the needed technologies and demonstrate a sub-microradian pointing capability under simulated spacecraft vibrations. This is expected to establish the foundation for future deep space optical communication missions. The pointing system, once built, should be able to support optical communications anywhere within solar system for non-orbiting spacecraft. The proposed pointing system is based on high precision inertial sensors and large format focal plane arrays, which can operate under low intensity beacon sources such as stars. This design concept drastically deviates from the conventional design limited for short range, which assumes high signal level and quadrant detectors or small format focal plane arrays. We will present the architecture of the pointing system, pointing error analysis, and the progresses on the laboratory validations.

Keywords: optical communications, tracking, pointing

1. INTRODUCTION

The objective of our effort is to design, analyze, and validate a pointing system for deep space optical communications. The requirements on pointing error depend on the downlink beam divergence that is a function of both beam wavelength and telescope aperture size. In the past, aperture sizes of 10 to 30 cm with 1064 nm laser were assumed for deep space optical communication mission studies, for example, 20 cm for a Mars mission and 30 cm for Europa mission studies [1, 2]. For the Europa mission studies, the allowable pointing loss was set to 2 dB or 0.47μrad (1-sigma value) in dynamic pointing error for downlink beam of 6.3μrad divergence. For the Mars mission studies, 1.7, 1.2, and 0.7μrad were allocated for 10, 15, and 25cm telescopes, respectively. From these considerations, sub-microradian pointing becomes the enabling technology for the success of the deep-space optical communications.

The design of a stable and robust laser pointing system of the optical communications has long been challenged by the stringent requirement of pointing accuracy. The accuracy of a typical optical communications system needs to be maintained by three orders of magnitude better than that of typical RF communications system (assuming a spacecraft (S/C) vibration/disturbance bandwidth of several hundred Hertz).

Over the past decade, the design of JPL's optical acquisition, tracking and pointing architecture has evolved to encompass all deep-space ranges within the solar system. The driving factor behind this development is the non-existence of a high intensity reference source in deep space. The high intensity reference is a critical source of information for overcoming the two largest pointing errors: S/C vibration and the estimation of the receiver location. Current laser beacons do not have sufficient power to reach deep space. Alternative reference sources such as Earth or stars have their own strength and weakness [1, 7]. Therefore, there is no single light source that satisfies our criteria as a reference source. Under these conflicting conditions, a new architecture for the pointing system was proposed.

A combination of a low intensity reference source and measurements of S/C vibration could be used to provide equivalent pointing as a high intensity reference source. The resulting constraint from the reference source and the addition of S/C vibration measurements motivated us to propose the new architecture of the pointing system for deep space missions. Our approaches for demonstrating the pointing system were divided into three phases: design, analysis, and laboratory validations.

The outline of the paper is as follows. In section 2, a summary of the design that discusses the architecture of the pointing system is presented. In section 3, the analysis results on pointing error sources will be presented to show that the sub-microradian pointing requirements can be met. Section 4 briefly explains the status of our activities on key technology developments for laboratory validations of the proposed pointing system.

2. POINTING SYSTEM ARCHITECTURE

Figure 1 shows the diagram and the information flow among the key elements of the pointing system. A typical operating scenario is as follows: the pointing offset is computed from the telescope attitudes and the receiver location. The computed pointing offset is used to command the high bandwidth steering mirror to direct the downlink laser beam. The telescope attitudes are estimated from the S/C vibration measurements. The receiver location is estimated from the centroids of a reference source seen on FPA (Focal Plane Array) and measurements of S/C vibrations. The role of the S/C vibration measurements is to compensate for the smearing and jitter of the beacon during the long exposure of the FPA due to the low intensity of a reference. This compensation is done through the enhanced centroid measurement processing which makes use of the jitter and motion during image exposure. The S/C vibration (high frequency vibration) may need to be dampened to meet the stringent pointing error budget.

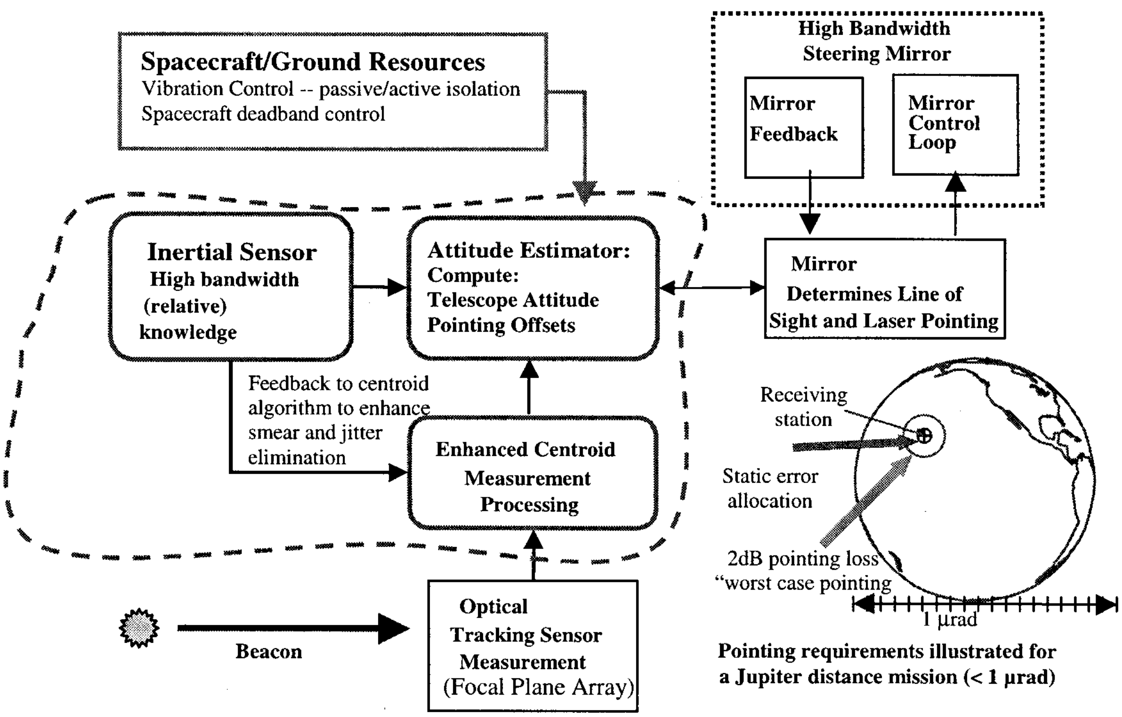

Figure 1. Baseline architecture of the proposed pointing system

In order to meet sub-microradian pointing requirements, the key pointing system elements should perform with high precision over a broad bandwidth. These elements are the inertial sensors, the FPA, and the steering mirror. The accuracy of the inertial sensors depends on the frequency response over the range of the vibration spectrum, electronic random noise from both the sensor and the sampling device, and any error from the algorithm that performs filtering and/or integration. The challenges have been in developing the integration and calibration algorithms for the initial velocity estimation, compensation for acceleration bias and scale factor bias. The main role of FPA is to collect photons from the low intensity reference and transfer the high SNR signal to the sampling device, which will be used by the enhanced centroid algorithm to produce an accurate estimate of the reference position on FPA. The critical parameters of FPA are low read noise and subwindow read capability at relatively high speed. The challenge on the steering mirror is the rejection of S/C vibration on the line of sight (LOS) of the downlink beam. This requires the high bandwidth closed control loop, which can be achieved with the proper design of a mirror driver (controller).

3. POINTING ERROR ANALYSIS

There are various pointing error sources that can be classified into three groups (Figure 2). The RSS (Root-Sum-Squared) value of the total dynamic pointing error was allocated to meet the sub-microradian pointing requirement. The error allocation has been done using our recently developed simulation tool, ATLAS (Acquisition Tracking Link Analysis Software). The details of the pointing error analysis can be found in [1]. The simulation results are based on the projected pointing system performance such as FPA read noise, closed control loop update rates, and inertial sensor (accelerometer) noise. These parameters are listed in Table 1. As indicated in Figure 2, the largest error comes from S/C vibrations, which is determined by the specific S/C vibration and the disturbance rejection of the tracking control loop. The second largest error source, inertial sensor noise, is mainly determined by the given noise specifications (Allied Signal QA-3000 accelerometer specifications used). The centroid errors on transmit laser (NEA, pixel-to-pixel non-uniformity, spatial quantization) are relatively smaller than those of the beacon since the transmit laser power on FPA can be easily controlled to meet the requirements.

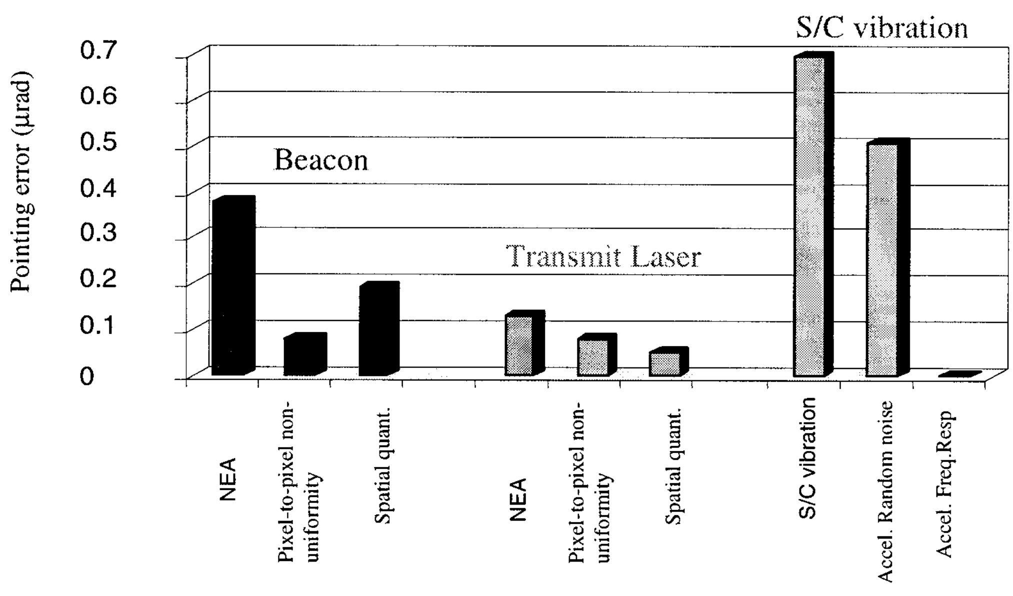

Figure 2. Pointing error allocations to various error sources using simulation results

Table 1. Pointing system parameters for the sub-microradian requirement

Beacon centroid error	
FPA read noise	50 e^-
FPA update rate	20Hz
Beacon signal/frame	10,000 e^-
Pixel-to-pixel non-uniformity	2%
Dynamic range	11bits
Transmit laser centroid error	
FPA read noise	200 e^-
FPA update rate	5kHz
Transmit laser signal/frame	400,000 e^-
Pixel-to-pixel non-uniformity	2%
Dynamic range	8bits
S/C vibration related parameters	
Closed control loop update rates:	5kHz
Inertial sensor (accelerometer) noise:	7.6μg (1-10Hz), 76μg (10-500Hz)
Inertial sensor frequency response error:	0.5% over 1-300Hz

4. PROGRESSES ON LABORATORY VALIDATIONS

In order to demonstrate the sub-microradian pointing capability, we have been working on several major technology developments. Brief status reports on each work area will be given here.

Inertial sensor algorithm developments: The objective of this activity is to achieve the feasible performance given by the inertial sensor (Allied Signal QA-3000 Accelerometer) noise specification. The angular displacement estimation error using QA-3000 specifications showed that the estimation error can be controlled within the pointing error budget [3, 4]. Emphasis has been placed on algorithm development for the double integration, initial velocity estimation, calibration for acceleration bias and scale factor bias. Double integration is necessary to go from acceleration to displacement. Functional demonstration has recently been completed using the developed algorithms [4]. Figure 3 shows the setup used for demonstration.

An example of the acceleroemter assisted tracking is illustrated in Figure 4b where the transmit laser tracks the beacon with a beacon update rate of only 200Hz. This can be compared with the performance when only the beacon measurements were used with a 1kHz update rate (Figure 4a). These two plots show similar tracking performance. Without inertial sensors, tracking performance from beacon measurements of 200Hz would be severely degraded. During functional demonstration, we experienced relatively high level of room vibrations that was on the order of 1mg which is more than ten times larger than the specificed accelerometer noise level. Several measures were implemented to isolate the room vibrations from the accelerometer output. These include turning off all air conditioners and all the equipment not used for the experiments. A floating table with pressurized air was also used. All these measures helped lower the noise level down to about 300μg from 1mg. Future work is to increase ADC (Analog-to-Digital Converter) resolution from 12 to 16 bits to reduce the quantization noise.

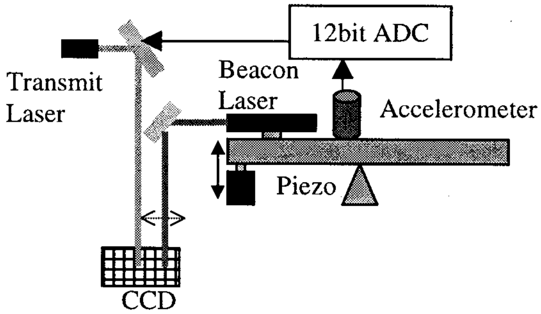

Figure 3. Setup for accelerometer-assisted tracking concept demonstration.

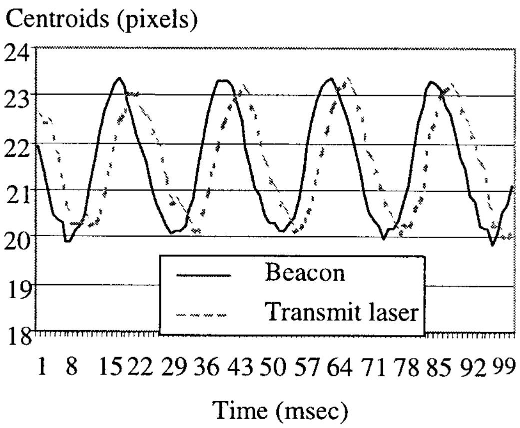

Figure 4a. Tracking with only the beacon at 1kHz with vibration signal of 45Hz.

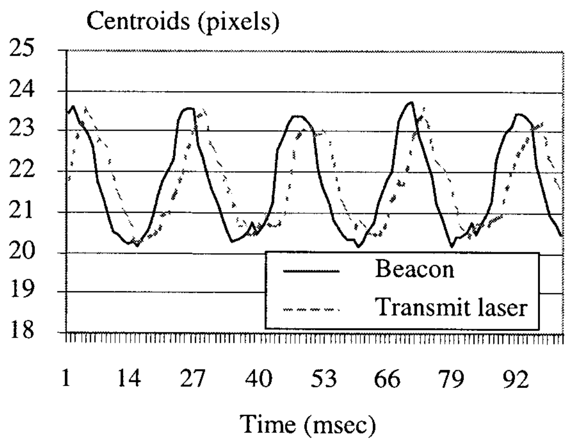

Figure 4b. Accelerometer assisted tracking with the beacon update rate of 200Hz and vibration signal of 45Hz

Development and validation of mirror driver for pointing control loop: The performance of the pointing control loop depends on the mirror performance (bandwidth, acceleration, residual jitter, etc), time delay (between incident beacon signal and application of the command signal), and mirror driver. The activity here focuses on designing a mirror driver (or controller) such that the overall disturbance rejection can be maximized given the expected S/C vibration spectrum. We have designed the mirror driver specifically for a LHD (Left Hand Design) mirror, model FO15, and achieved a rejection bandwidth of 70Hz using control update rates of 1kHz [5]. The final goal is to run at 5kHz and achieve rejection bandwidth of few hundred Hertz. Figures 5 and 6 show the diagram and the picture of the ATP (Acquisition, Tracking, and Pointing) tested optical setup. Significant hardware upgrades to meet our goals are underway.

High performance camera development: A low noise, high-speed camera development is the goal of this work area. After extensive surveys of many commercial FPAs, Texas Instruments CCD (TC237) was selected for our camera. This is a large format (640x480) CCD with low read noise features (< $20e^-$). Preliminary results exhibit readout rates of a single 8x8 subwindow close to 6kHz with 7-bits of resolution per pixel. Future work involves characterization of the optical qualities of the camera and improvement of the pixel dynamic range to 10 bits with a better ADC. Figure 8 show the sample image taken by the developed camera (Figure 7).

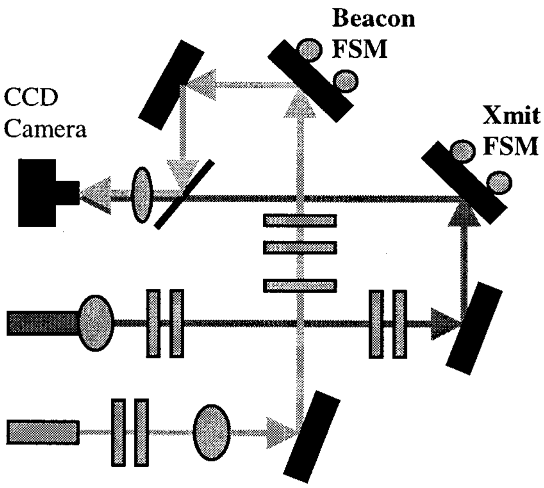

Figure 5. ATP Test Bed Optical Setup

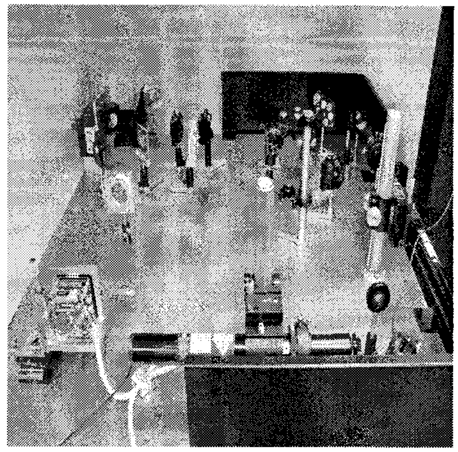

Figure 6. Photograph of the ATP Testbed Optical Setup

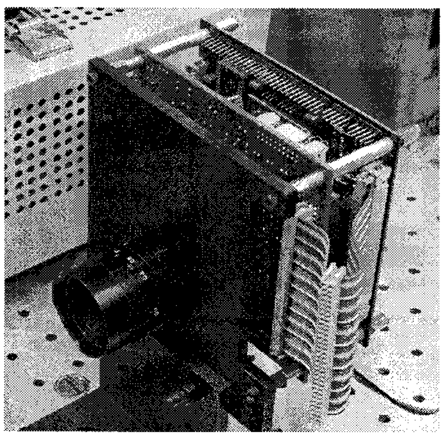

Figure 7. TC237 Camera

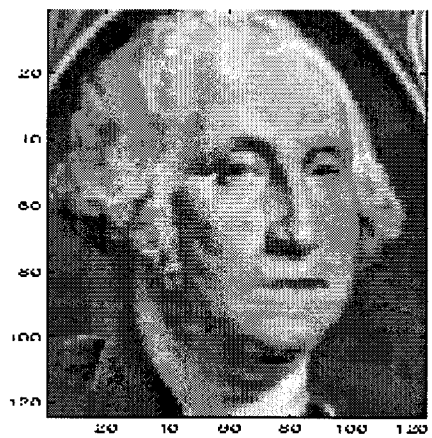

Figure 8. Sample image taken by TC237 camera

Development of vibration platform: The goal of the vibration platform is to provide simulated vibrations to the pointing system, which would represent the expected S/C vibrations. The benefit of this capability is to enable the validation of the pointing system in a laboratory. This activity consists of platform development (H/W) and algorithm development to synthesize the vibration signal that will be used to drive the actuator. The platform consists of a 61 cm x 61 cm optical breadboard mounted on a ball bearing pivot that is driven by a single piezo-electric actuator (PZT). The PZT provides motion in a single axis, giving the platform approximately 200 μrad of angular motion with a bandwidth in excess of 100 Hz (Figure 9). We have completed characterization of the vibration platform. The platform is ready for use in Acquisition, Tracking, and Pointing (ATP) Testbed. Details of the vibration platform can be found in [8].

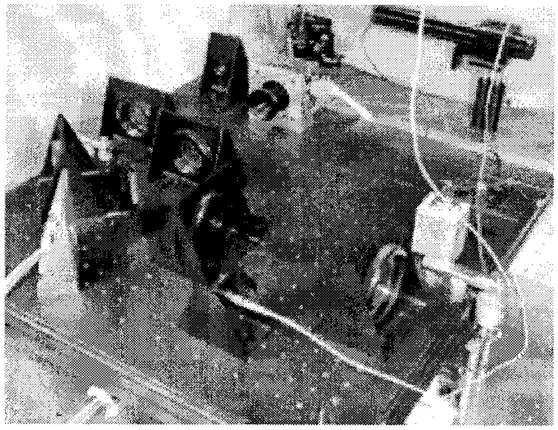

Figure 9. Vibration platform

5. CONCLUSION

We have presented the architecture of the sub-microradian pointing system for deep space optical communications with the analysis of the various pointing errors. The new pointing system architecture would allow stable pointing operations even under low intensity reference sources by employing inertial sensors, which is critical for deep space missions where the high intensity optical reference sources are not readily available. We are currently developing several key technologies for laboratory demonstrations under the simulated S/C vibration environments.

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